

## Tactile estimation of the roughness of gratings yields a graded response in the human brain: an fMRI study

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Human subjects can tactually estimate the magnitude of surface roughness. Although many psychophysical and neurophysiological experiments have elucidated the peripheral neural mechanisms that underlie tactile roughness estimation, the associated cortical mechanisms are not well understood. To identify the brain regions responsible for the tactile estimation of surface roughness, we used functional magnetic resonance imaging (fMRI). We utilized a combination of categorical (subtraction) and parametric factorial approaches wherein roughness was varied during both the task and its control. Fourteen human subjects performed a tactile roughness-estimation task and received the identical tactile stimulation without estimation (no-estimation task). The bilateral parietal operculum (PO), insula and right lateral prefrontal cortex showed roughness-related activation. The bilateral PO and insula showed activation during the no-estimation task, and hence might represent the sensory-based processing during roughness estimation. By contrast, the right prefrontal cortex is more related to the cognitive processing, as there was activation during the estimation task compared with the no-estimation task, but little activation was observed during the no-estimation task in comparison with rest. The lateral prefrontal area might play an important cognitive role in tactile estimation of surface roughness, whereas the PO and insula might be involved in the sensory processing that is important for estimating surface roughness.

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### Introduction

In all sensory modalities, humans are capable of making order of the physical world with regard to different perceptual dimensions, such as loudness, odor, brightness, and pitch. The current study focuses on surface roughness, which is a perceptual dimension that is highly salient to the sense of touch. To date, many psychophysical and neurophysiological experiments have been elucidating the peripheral neural mechanisms that underlie tactile roughness estimation (e.g., Johnson et al., 2002); however, as yet, the associated cortical mechanisms are not well understood. The only direct investigation into the human cortical mechanisms underlying the tactile estimation of surface roughness was conducted by Burton et al. (1997), who used positron emission tomography (PET) to compare regional cerebral blood flow (rCBF) during a roughness-estimation task with tactile gratings relative to a baseline (rest) condition.

The estimation of tactile roughness requires both sensory and cognitive-based processing; the latter serves to compare the ongoing roughness sensation with past sensory experience. In a PET study, the somatosensory areas, such as the primary somatosensory area (SI) and parietal operculum (PO), were activated during a tactile roughness-estimation task relative to a baseline (rest) condition (Burton et al., 1997). Furthermore, SI, the PO, and insula were all activated by the passive vibratory stimulation compared to a baseline condition (rest) (Burton et al., 1993; Coghill et al., 1994; Francis et al., 2000). These results indicate that moving surface textures provide vibratory stimuli on the skin surface, which in turn activate these somatosensory areas. PET studies also showed that the PO was activated specifically by a tactile roughness-discrimination judgment, as compared to the discrimination of length or shape (Ledberg et al., 1995; Roland et al., 1998).

By contrast, the lateral prefrontal cortex is related to several types of tactile discrimination. This area was activated during the

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tactile discrimination of the speed of a rotating brush on the palm (Bodegard et al., 2000), the tactile discrimination of how oblong parallelepipeds were (Stoekel et al., 2003) and the discrimination of two-dot Braille characters in normal subjects (Harada et al., 2004). These findings suggest that the tactile-discrimination processes, possibly including roughness estimation, are organized hierarchically, such that the sensory and cognitive processes correspond to the somatosensory areas and prefrontal cortices, respectively.

The main objective of our study was to identify the neural correlates of both the sensory and cognitive-processing stages of tactile roughness estimation. Our hypothesis was that the sensory processing takes place in the somatosensory areas, whereas the cognitive processing involves the prefrontal cortices. We used functional magnetic resonance imaging (fMRI) to examine the blood oxygen level-dependent (BOLD) signal of subjects when they performed a tactile roughness-estimation task and when they received the identical tactile stimulation passively (no-estimation task). The conventional categorical approach (the contrast of the no-estimation task vs. rest) should reveal the regions representing the sensory-based processing. Similarly, contrasting the estimation vs. no-estimation tasks should reveal the neural underpinnings of the cognitive processing.

In addition, attention to touch is necessary to conduct the roughness-estimation task. When brain activity is recorded during the task with fMRI, different types of signals correspond to the activation of the attentional mechanism and its interaction with the sensory and cognitive systems (Corbetta, 1998). To differentiate them, we also employed a parametric factorial design, wherein roughness was varied under the task and control conditions (Friston et al., 1997). Underlying premise is that activation of the attentional mechanism is condition-dependent (i.e., estimation vs. no-estimation), whereas its interaction with the sensory and cognitive processes of roughness estimation is dependent on roughness magnitude (roughness-related activation; negatively or positively graded activity in relation to surface roughness). Thus, the neural substrates of the roughness estimation are expected to reveal roughness-related activation during the estimation condition, whereas not during the no-estimation condition.

## Materials and methods

### Subjects

Fourteen healthy volunteers (12 male and 2 female) aged 23–26 years participated in the fMRI study. All of them are right-handed according to the Edinburgh's handedness inventory (Oldfield, 1971). All subjects gave informed written consent and the study was approved by the Ethics Committee of Human and Animal Experiments at Kyoto University, Japan, and the ethical committee of the National Institute for Physiological Sciences. None of the volunteers had a history of symptoms requiring neurological, psychological, or other medical care.

### Stimulus application

A professional stamp craftsman created the linear gratings stimuli from plastic sheets with a photosensitive layer (Makoto Craft, Yokohama, Japan). The four different stimuli consisted of three gratings with different spatial periods, defined as the distance

between the centers of two ridges (approximately 0.5, 1.2, and 1.8 mm), and one flat surface without any groove. The height and width of the ridge was 1.0 and 0.2 mm, respectively. Each oblong-shaped grating was glued to one quarter of a plastic disc (radius 60.0 mm; Fig. 1A). A wooden dowel was attached vertically to the center of the disk and was used by the experimenter to rotate the disc horizontally (Fig. 1B).

The subjects lay supine on a bed with their eyes closed and their ears plugged, and were instructed to relax. Their right arm was extended to the side of their body and comfortably supported by a cushion. The subjects lightly placed their right middle fingertip on the stimulus disk, with the index and ring fingers on a plastic frame just above the surface. Proximal–distal distance from the tip of the middle finger was approximately 1.5–2.0 cm, depending on the subject. Adhesive tape was applied to the nail of the middle finger, so that the finger was immobilized horizontally. Each end of the adhesive tape was attached to the plastic frame. Subjects were asked to maintain the middle finger lightly on the stimulator. We made it clear to the subjects that they should avoid applying excessive pressure to the stimulator. Subjects neither reported nor complained of any pain when the gratings were presented during the experiment.

The experimenter did not observe any conspicuous movement in any subject when presenting the stimuli to the fingertip. To ensure that there was no invisible extra muscle activity of the middle finger that might have affected the BOLD signals in the somatosensory areas, we also recorded the electromyogram (EMG) activity of the flexor digitorum superficialis (FDS) and second dorsal interosseous (SDI) muscles throughout the fMRI experiment. After the end of the experiment, EMG activities of the FDS and SDI muscles during the flexion and abduction of the right middle finger were recorded for each subject under the same condition of the functional image acquisition. This was to exclude the right middle finger movement during the experiment. Despite of electric noise due to image data acquisition, the existence of EMG activity could be evaluated (Fig. 2A). We confirmed that all subjects had applied negligible vertical and horizontal force with their middle finger during the experiment.

A highly trained experimenter rotated the dowel clockwise and anticlockwise periodically. The range of rotation across each stimulus was approximately 80°, and was demarcated with black ink on each stimulus disc. The mean speed of each rotation, which was guided by auditory cues, was 0.7 Hz (110°/s). Only the experimenter heard the auditory cues through a pair of ceramic-condenser headphones (Hitachi Medical Corporation, Tokyo, Japan).

### Training behavioral task

All the subjects in the fMRI experiment received a short training session lasting less than 30 min roughly 1 week before the fMRI experiment. Only the training data of the 12 subjects are reported, as the data for the other two subjects were not recorded. Subjects were given a reference stimulus (flat surface) for 4 s during the 6-s reference period. After the 4-s stimulation interval, the experimenter displaced the finger slightly and changed the surface by rotating the stimulator for less than 2 s. This indicated to the subjects that the reference stimulation had ended. Next, one of the three test stimuli varying in physical magnitude (that is, spatial periods of 0.5, 1.2, and 1.8 mm) was applied to the same volar

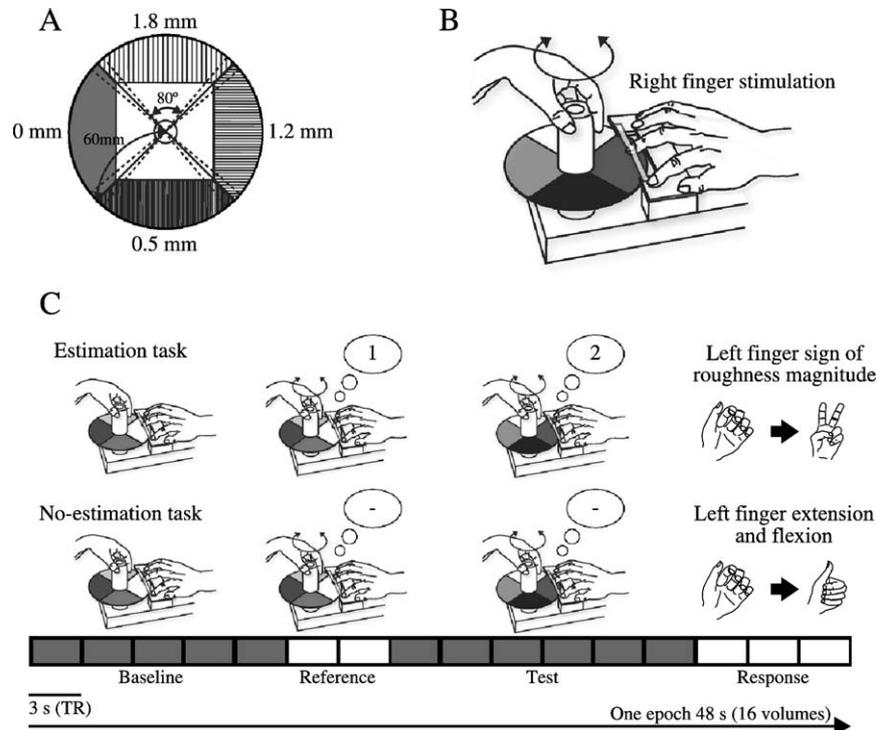


Fig. 1. Materials and experimental design for the fMRI experiment. (A) Tactile roughness stimuli. The gratings contained a series of vertical bars with different spatial periods: 1.8, 1.2, and 0.5 mm for test stimuli, and a flat surface for the reference stimulus. (B) Stimulus application. The experimenter rotated each stimulus under the subject's right middle finger within  $80^\circ$  of each sector at 0.7 Hz. (C) Experimental design. The fMRI design included four periods (baseline, reference, test, and response) per each experimental block of 48 s. The subject was instructed to estimate roughness in the test period of the estimation task and simply to attend to the stimulus in the no-estimation task. After stimulation, the subject either reported the roughness magnitude using the left hand in the estimation task, or extended the left thumb and flexed the other left fingers in the no-estimation task. We focused our analysis on the test and baseline periods (gray areas).

surface for 5 s (test period). The subjects were asked to make a categorical estimate regarding the test stimuli in terms of a 10-point scale (with increasing numbers indicating greater roughness). The reference surface was designated as having a roughness of "1". The subjects indicated the magnitude of the roughness by the signs with their left hand within the next 9 s (response period). The subjects were trained to make finger signs until they became comfortable doing so. A second experimenter recorded the finger responses. During the response period, the stimulated middle finger was returned to the reference surface. Presentation of each surface was repeated seven times in a pseudo-randomized order for each subject and the latter five trials in each surface were recorded. The stimuli were always presented from one of the demarcated ends of each test surface.

#### fMRI study

##### Estimation task

The design of the estimation task was almost identical to that of the training task, except for the duration of tactile stimulation and the added baseline period (Fig. 1C). A single experimental block included baseline (15 s), reference (6 s), test (18 s), and response (9 s) periods. For the estimation task, we chose a long duration for the test period because a minimum of 10 s was required to examine significantly graded activity due to electro-tactile stimulation in primary somatosensory cortex (SI) (Krause et al., 2001) and this might hold true for other somatosensory areas. The subjects were instructed to confirm the current roughness rating during the rest of

18 s, if they finished estimating the surface roughness before the offset of a test stimulus. The subjects were in static contact with the reference surface during the 15 s baseline period. Each of the three roughness surfaces was applied four times in a pseudo-randomized order. Over the entire experiment, 192 functional images (4 repetitions  $\times$  3 magnitudes  $\times$  16 images per block) were collected in each task for each subject (3 s per image).

##### No-estimation task

The design of the no-estimation task was almost the same as the estimation task, except that subjects were instructed not to estimate the magnitude of roughness in the test period. Instead, subjects were instructed to simply attend to the stimuli during that time. At stimulus offset, subjects were asked to respond by extending their left thumb and flexing the other left fingers. The estimation and no-estimation tasks were performed in separate sessions for each subject.

##### Data acquisition and processing

Surface EMG signals of the FDS and SDI muscles were recorded with a pair of dish-shaped electrodes specialized for use with MRI (NE-703A, Nihon Koden, Tokyo, Japan). The EMG signals were sampled at 2,000 Hz with 16-bit resolution, and acquired with a PC (Inspiron 8000, DELL, Round Rock, TX, USA) through an amplifier (MEG6100-M, Nihon Koden) and an external A/D converter (Powerlab 16SP, ADInstruments, Colorado Springs, CO, USA). The EMG signals were filtered with a 1.5–

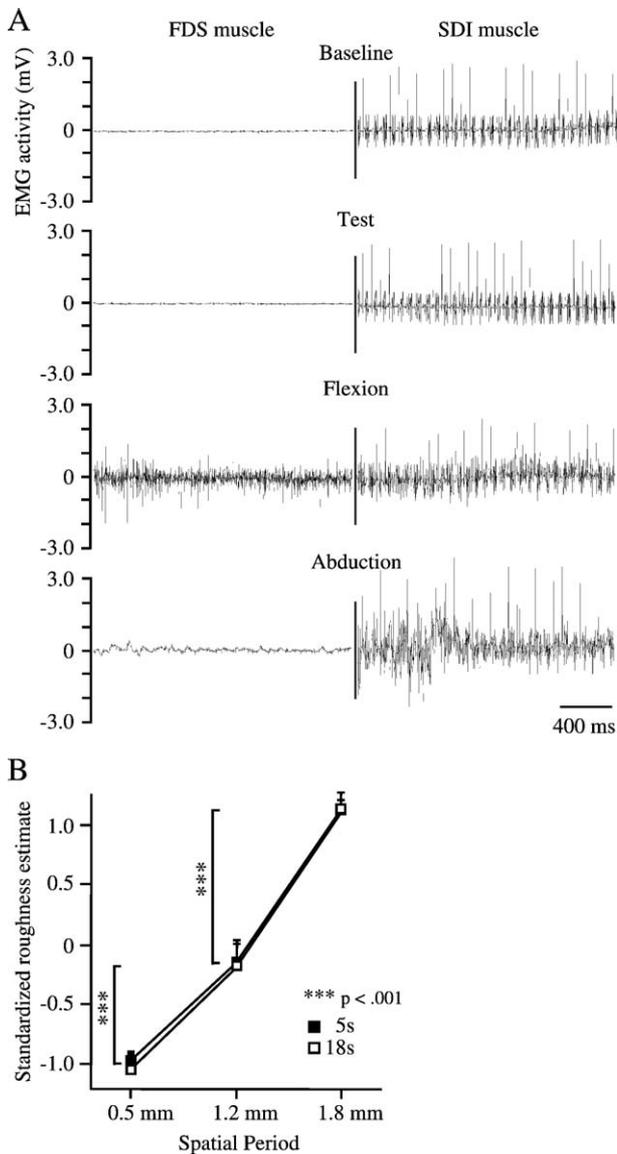


Fig. 2. Behavioral results. (A) An example of typical EMG data of the flexor digitorum superficialis (FDS, left column) and the second dorsal interosseous (SDI, right column) muscles of the right hand. EMG activities were recorded during the test (top row) and baseline (second row) conditions of the fMRI experiment, and during the flexion (third row) and abduction (bottom row) of the right middle finger under the same condition of functional imaging data acquisition, and hence similar patterns of sharp and regular noise due to EPI are noted across the conditions in each muscle. The EMG activities in the test and baseline periods were negligible compared with the flexion and abduction conditions. (B) The roughness magnitude estimation in the training (5 s) and the fMRI experiment (18 s). Ratings in each subject were standardized. Error bars indicate SD. Tukey's HSD test for multiple comparisons showed a significant difference between the three different stimulus surfaces of gratings ( $P < 0.001$ ).

3,000 Hz bandpass filter. The acquired data were processed further with a Windows-based software (Chart v4.2; ADInstruments).

Functional MR images were acquired on a 3 T head scanner (Allegra, Siemens, Erlangen, Germany) with echo planar imaging (EPI) capability. Standard sequence parameters were used for obtaining functional images: gradient-echo EPI, TR = 3,000 ms, TE = 30 ms, flip angle =  $85^\circ$ , 44 axial slices of 3 mm thickness

with no interslice gap, FOV =  $192 \times 192$  mm, and in-plane resolution =  $3.0 \times 3.0$  mm. After the acquisition of functional images, T1-weighted high-resolution anatomical images were obtained (voxel size =  $0.9 \times 0.9 \times 1$  mm).

Image processing and statistical analysis were performed with the Statistical Parametric Mapping package (SPM99; <http://www.fil.ion.ac.uk/spm>; Wellcome Department of Cognitive Neurology, London, UK) implemented in MATLAB (Mathworks Inc., Sherborn, MA, USA) (Friston et al., 1995a,b).

Realigned images were normalized to a standard EPI template image as defined by the Montreal Neurological Institute (MNI) that closely approximates the space described in the atlas of Talairach and Tournoux (1988). The normalized EPI images were filtered using a Gaussian kernel of 8 mm (full width at half maximum; FWHM) in the  $x$ ,  $y$ , and  $z$  axes. The T1-weighted high-resolution anatomical images also were normalized by the same procedure.

#### Statistical analysis

The numeric roughness estimates of each subject in training and during the fMRI study were standardized. The standardized roughness magnitude estimates of all subjects were collected and statistically evaluated with SPSS software (Version 10.0J; SPSS Japan Inc., Tokyo, Japan).

We fitted a general linear model (GLM) to the pooled functional MRI data from all subjects (fixed-effect model) to increase the sensitivity of the analysis (Friston et al., 1995b; Worsley and Friston, 1995). The time series for each voxel was high-pass filtered to 1/96 Hz and low-pass filtered by a canonical hemodynamic–response function. The neural activities for each of the reference, test and response periods were modeled with each box-car function convolved with a canonical hemodynamic–response function. Two sessions were included in the group-design matrix for the estimation and no-estimation tasks. The resulting design matrix for the group analysis had 28 sessions with 14 subjects. Each session included three regressors for the reference, test and response periods.

#### Categorical analysis

To assess the mean activation across the spatial periods of the gratings, we implemented a linear contrast of the test period vs. baseline in the estimation task, the same contrast in the no-estimation task, and a contrast of the test period of the estimation task vs. the test period in the no-estimation task (estimation vs. no-estimation). The resulting SPM  $\{T\}$  for these contrasts was thresholded at  $T_{2215,1} = 3.09$ . We reported brain regions with a significant  $P < 0.05$  at the cluster level corrected for multiple comparisons (Friston et al., 1996).

To define the somatosensory areas during the no-estimation task, we first evaluated the contrast for the no-estimation vs. baseline conditions. Then, in order to define areas more active by the estimation than the no-estimation condition, we performed the contrast of the estimation vs. no-estimation within the areas that were active for the contrast of the estimation vs. baseline.

#### Parametric factorial analysis

To reveal brain areas that co-varied with the spatial periods of the grating stimuli, we performed parametric-modulation analysis (Buchel et al., 1998). The positive  $t$  contrast of the parametric

modulation between the two tasks yields a positive difference in the slope of the graded activity, while the negative  $t$  contrast of the parametric modulation between the two tasks yields a negative difference in the slope of the graded activity. A regressor for parametric modulation was added to the test period for each session of each task. We used the linear parameters ( $-1$ ,  $0$ , and  $+1$ ) as parametric modulators for the spatial periods ( $0.5$ ,  $1.2$ , and  $1.8$  mm) in both the estimation and no-estimation tasks. The regressor for parametric modulators was orthogonalized to the regressor for the test period.

The analysis was conducted separately in two of the areas depicted by the categorical analysis: areas that were active in the no-estimation task (the contrast of the no-estimation vs. baseline) and areas that were more active in the estimation task (the contrast of the estimation vs. no-estimation inclusively masked by the estimation vs. baseline). We assessed the positively and negatively graded activity within those areas for each task by performing the appropriate contrasts. Finally, we compared the slope of the graded activity between the estimation and no-estimation tasks within areas showing graded activity in the estimation task.

#### VOI-based group analysis

To confirm the result of the categorical and parametric factorial analyses above, we further implemented a volume-of-interest (VOI) analysis using the MARSBAR procedure from the SPM99 toolbox (Brett et al., 2002). The data were extracted as filtered raw data from areas depicted by the contrast in the parametric modulation analysis between the estimation and no-estimation conditions within the areas with graded activity in the estimation task found during the SPM fixed-effect group analysis.

To calculate the percent signal change, we first calculated the mean signal value of the two baseline periods that occurred before and after a specified test period. Then, the percent signal change in each test period was calculated as follows: ((mean

signal in a specified test period – mean signal averaged over the two baseline periods)  $\times 100$  / (mean signal averaged over the two baseline periods). Only the mean signal value in the baseline period before the test period was utilized to calculate the percent signal change in the last test period. The first two scans in each period of each epoch were excluded from this analysis. The percent signal change in each VOI was evaluated statistically by an analysis of variance (ANOVA) with two factors, task (estimation and no-estimation) and spatial period ( $0.5$ ,  $1.2$ , and  $1.8$  mm).

As an alternate statistical method to assess the occurrence of graded activity across subjects, the slope of the linear function was fitted to the percent signal change as a function of spatial period for each VOI area in each subject. One-sample  $t$  tests were performed on these slopes to test the hypothesis that each slope was either greater or less than zero.

## Results

### Behavioral results

In both the behavioral training and the fMRI experiment, subjects accurately ordered the gratings by magnitude of roughness (Fig. 2B). Two-way ANOVAs (three spatial periods:  $0.5$ ,  $1.2$  and  $1.8$  mm)  $\times$  (two stimulus length:  $5$  s for training and  $18$  s for fMRI experiment) of the roughness rating indicated a significant effect of the spatial period ( $F_{2, 22} = 795.0$ ,  $P < 0.001$ ). Tukey's HSD test for multiple comparisons showed significant differences between all stimulus combinations ( $P < 0.001$ ).

### fMRI results

Table 1 shows the coordinates of the foci in the significantly activated areas. In accordance with our hypothesis, the no-

Table 1  
Task-related mean activity

Anatomical region	BA	Side	$x$	$y$	$z$	$T_{2215,1}$	BA	Side	$x$	$y$	$z$	$T_{2215,1}$
	No-estimation vs. baseline						Estimation vs. no-estimation					
Postcentral gyrus	3	L	-60	-22	44	11.89						
Parietal operculum/insula	48	L	-58	-20	18	14.05	48	L	-64	-16	12	4.19
	48	R	58	-22	18	9.24						
Frontal operculum/insula	48	L	-58	10	-2	8.02	47	L	-32	20	-2	7.01
	48	R	50	14	10	7.12	47	R	30	24	4	6.01
Lateral prefrontal areas	10	L	-34	52	20	7.49	46	L	-44	28	28	5.72
	10	R	36	54	10	7.03	46	R	44	34	22	6.39
Orbitofrontal areas	11	L	-30	52	-14	4.74						
	47/46	R	44	48	-8	4.55	10	R	36	58	-4	5.18
Medial frontal areas	6	L	-2	-2	64	10.01	32/8	L	-4	18	46	6.89
	6	R	2	10	56	8.52	32/8	R	6	24	44	6.25
Lateral frontal areas	6	L	-46	-12	58	9.49	9	L	-46	6	28	6.27
	6	R	58	6	40	7.59	9	R	60	18	26	5.69
Posterior parietal areas	40	L	-44	-44	62	7.1	40	L	-44	-42	40	6.51
	40	R	60	-32	50	5.85	7	R	38	-66	52	6.75
Precuneous	7	L	-6	-76	52	4.29						
	7	R	16	-74	38	4.22						
Basal ganglia		L	-20	2	0	6.01						
		R	18	0	20	4.15						
Cerebellum		L	-42	-72	-28	6.93						
		R	20	-72	-22	8.17		R	10	-80	-48	4.83

BA, Brodmann area; R, right hemisphere; L, left hemisphere;  $x$ ,  $y$ , and  $z$  are stereotaxic coordinates (mm).  $P < 0.05$  corrected at cluster level.

estimation vs. baseline contrast significantly activated several somatosensory areas; namely, the contralateral postcentral gyrus (presumably SI), bilateral parietal operculum (PO), and bilateral insula (Fig. 3, top). In addition, the no-estimation task significantly activated the frontal areas, including the supplementary motor area and lateral premotor areas, lateral prefrontal areas, frontal operculum, posterior parietal cortices, precuneus and subcortical areas, such as the cerebellum and basal ganglia, bilaterally (Table 1 and Fig. 3, top).

The estimation vs. no-estimation contrast inclusively masked by the estimation vs. baseline contrast significantly activated the prefrontal areas including the bilateral medial prefrontal areas, bilateral lateral prefrontal areas, right orbitofrontal area and

bilateral frontal operculum, bilateral posterior parietal areas, left lateral parietal operculum, and right cerebellum (Table 1 and Fig. 3, bottom).

#### Graded responses in areas activated by tactile stimuli

Table 2 lists the coordinates of the foci that showed graded activity for each task within the areas activated by the no-estimation task. Within these areas, in the estimation task, negatively graded activity was found in the left medial PO/insula and right lateral PO (Table 2 and Fig. 4A, blue-colored area). By contrast, in the no-estimation task, no conspicuously graded activity was observed.

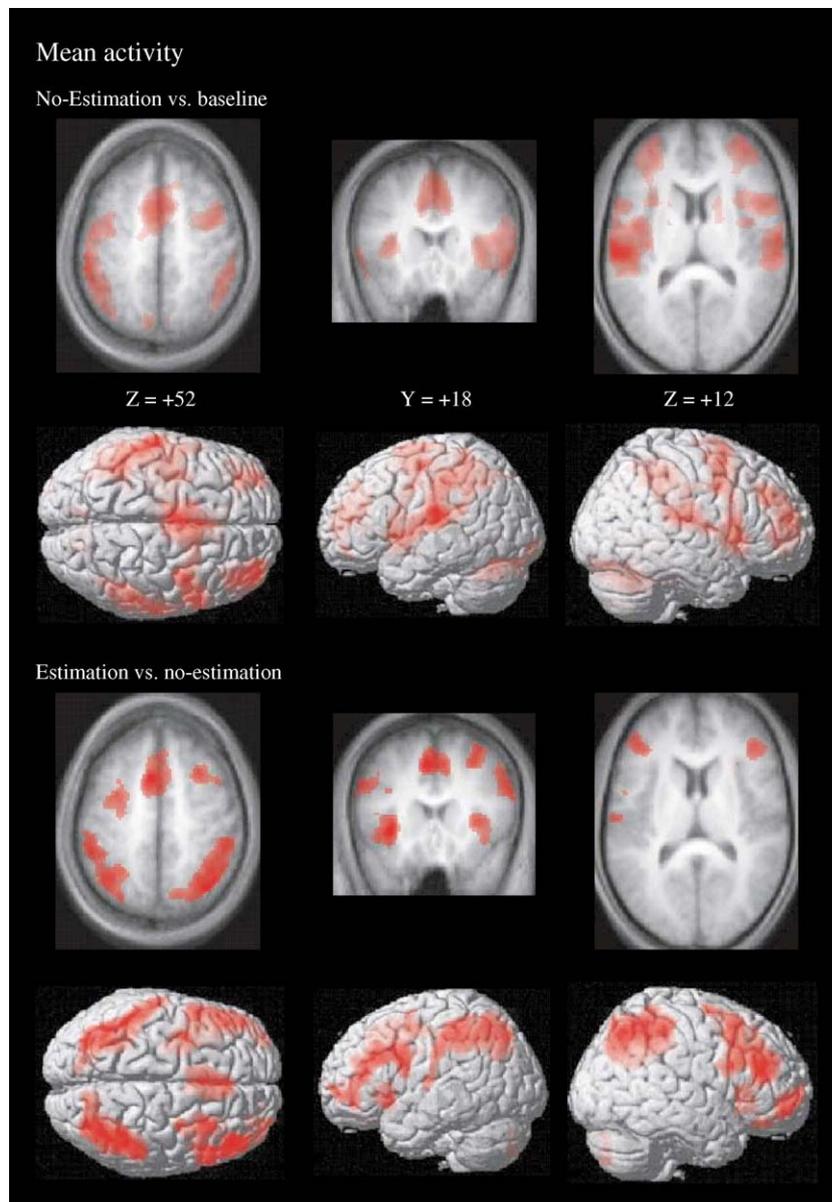


Fig. 3. Statistical parametric maps of categorical analysis of neural activity during the no-estimation condition (compared with baseline, upper rows) and during the estimation condition (compared with the no-estimation, masked by the estimation vs. baseline, lower rows). Task-related increases in MR signal were superimposed on transaxial ( $z = +52$  mm, left;  $z = +12$  mm, right) and coronal ( $y = +18$  mm, middle) sections of mean T1 weighted high resolution MRI of the participants of the present study (top and third rows), and on a surface-rendered high resolution MRI of the subject unrelated to the present study (second and bottom rows). Corrected  $P < 0.05$  at the cluster level.

Table 2  
Graded activity in areas activated by the no-estimation vs. baseline

Task	Side	x	y	z	T <sub>2215,1</sub>	Volume	Slope
Estimation							
Medial PO/insula	L	-36	-10	10	4.77	1720	-
Lateral PO	R	58	-6	6	4.36	3920	-
No-estimation	n.s.						
More graded activation in the estimation than no-estimation							
Medial PO/insula	L	-34	-10	10	4.44	896	-
Lateral PO	R	64	-6	4	3.76	1112	-

R, right hemisphere; L, left hemisphere; x, y, and z are stereotaxic coordinates (mm).

Volume was calculated in mm<sup>3</sup>.  $P < 0.05$  corrected at cluster level. -, negatively graded activities; PO, parietal operculum; n.s., not significant.

The left medial PO/insula and right lateral PO revealed significantly steeper slope of the graded activity during the estimation task than the no-estimation task (Table 2 and Fig. 4A, red-colored area).

#### Graded responses in areas more activated by the estimation task than the no-estimation task

Table 3 lists the coordinates of the foci that showed graded activity within the areas activated by the cognitive process of tactile roughness estimation (the contrast for the estimation vs. no-estimation inclusively masked by the estimation vs. baseline). The right lateral prefrontal area (Brodmann area (BA) 46) showed negatively graded activity (Table 3 and Fig. 4B, blue-colored area). The right lateral prefrontal area also revealed significantly steeper slope of the graded activity during the estimation task than the no-estimation task (Fig. 4B, red-colored area).

#### VOI analyses

The VOI analyses confirmed the results of the group analyses above. In the left medial PO/insula and the right lateral PO, negatively graded signals were found consistently during the estimation task, whereas no such graded activity was observed during the no-estimation task (Fig. 4C, top and middle and Fig. 5, top). A two-way ANOVA ((two tasks: estimation and no-estimation)  $\times$  (three spatial periods: 0.5, 1.2, and 1.8 mm)) of the percent signal change yielded a significant interaction between the two factors ( $F_{2,26} = 5.20$ ,  $P = 0.013$  for the left PO/insula; and  $F_{2,26} = 5.29$ ,  $P = 0.012$  for the right PO), but no significant difference between the tasks. There was a significant simple main effect of spatial periods only in the estimation task ( $F_{2,26} = 9.76$ ,  $P < 0.001$  for the left PO/insula; and  $F_{2,26} = 7.43$ ,  $P < 0.01$  for the right PO). Tukey's HSD tests for multiple comparisons in the estimation task showed a significant difference in the percent signal change between 0.5 and 1.8 mm ( $P < 0.001$ ) and a non-significant trend toward significance between 0.5 and 1.2 mm ( $P = 0.065$ ) in the medial left PO/insula. In the lateral right PO, there was a significant difference between 0.5 and 1.8 mm ( $P < 0.01$ ), and a non-significant trend toward significance between

0.5 and 1.2 mm ( $P = 0.055$ ) in the estimation task. These results confirm the occurrence of significant graded activity during the estimation task within the left medial PO/insula and right lateral PO.

The right lateral prefrontal area also showed negatively graded activity only in the estimation task, whereas there was almost no signal increase during the no-estimation task (Fig. 4C, bottom and Fig. 5, left bottom). The identical ANOVA showed a significant difference in the percent signal change between the tasks ( $F_{1,13} = 13.9$ ,  $P < 0.01$ ) and a significant interaction between the two factors ( $F_{2,26} = 5.66$ ,  $P < 0.01$ ). There was a simple main effect of spatial periods only in the estimation task ( $F_{2,26} = 15.64$ ,  $P < 0.0001$ ). Tukey's HSD test showed a significant difference between 0.5 and 1.8 mm ( $P < 0.001$ ) and between 1.2 and 1.8 mm ( $P < 0.01$ ) in the estimation task. This result confirms the occurrence of significant graded activity during the estimation task within the right lateral prefrontal area.

As a second statistical test of the consistency of the graded activities across subjects, we also performed one-sample  $t$  tests on the slopes of linear functions fitted to the percent signal change data as a function of increasing spatial period. The mean slopes for the linear functions were:  $0.016 \pm 0.152$  for the left PO/insula (mean and SD),  $0.021 \pm 0.298$  for the right PO and  $-0.01 \pm 0.274$  for the right lateral prefrontal area (no-estimation task); and  $-0.191 \pm 0.186$  for the left PO/insula,  $-0.364 \pm 0.359$  for the right PO and  $-0.332 \pm 0.253$  for the right lateral prefrontal area (estimation task). One-tailed  $t$  tests indicated that all slope values were significantly different from zero in the estimation task ( $t_{13} = 3.85$ ,  $P < 0.001$  for the left PO/insula;  $t_{13} = 3.79$ ,  $P < 0.01$  for the right PO; and  $t_{13} = 4.93$ ,  $P < 0.001$  for the right lateral prefrontal area). No such significant difference was observed in the no-estimation task ( $P > 0.3$ ). The collective results from the ANOVAs and one-sample  $t$  tests of the slopes provide converging evidence for the existence of graded activity in the left medial PO/insula, right lateral PO and right lateral prefrontal area during the roughness-estimation process.

#### Discussion

As expected, we found that the somatosensory areas showed activation during the no-estimation condition when compared with the resting condition. The parietal operculum (PO) and insula showed roughness-related activation only during the estimation task. By contrast, the lateral prefrontal cortex showed activation during the estimation task compared with the no-estimation condition. This area also showed roughness-related activation only during the estimation task.

#### Task design

The estimation task in our study includes sensory, cognitive (estimation) and motoric stages of processing. During the initial reference period, the subject's right middle finger was presented with a reference surface, together with a corresponding numeric estimate. During the following test period (the focus of our analysis), subjects were presented with a second surface and required to numerically estimate its roughness magnitude. Subjects scaled their roughness percept relative to the reference stimulus and to their sensory experience during earlier test periods. After scaling roughness magnitude, subjects had to

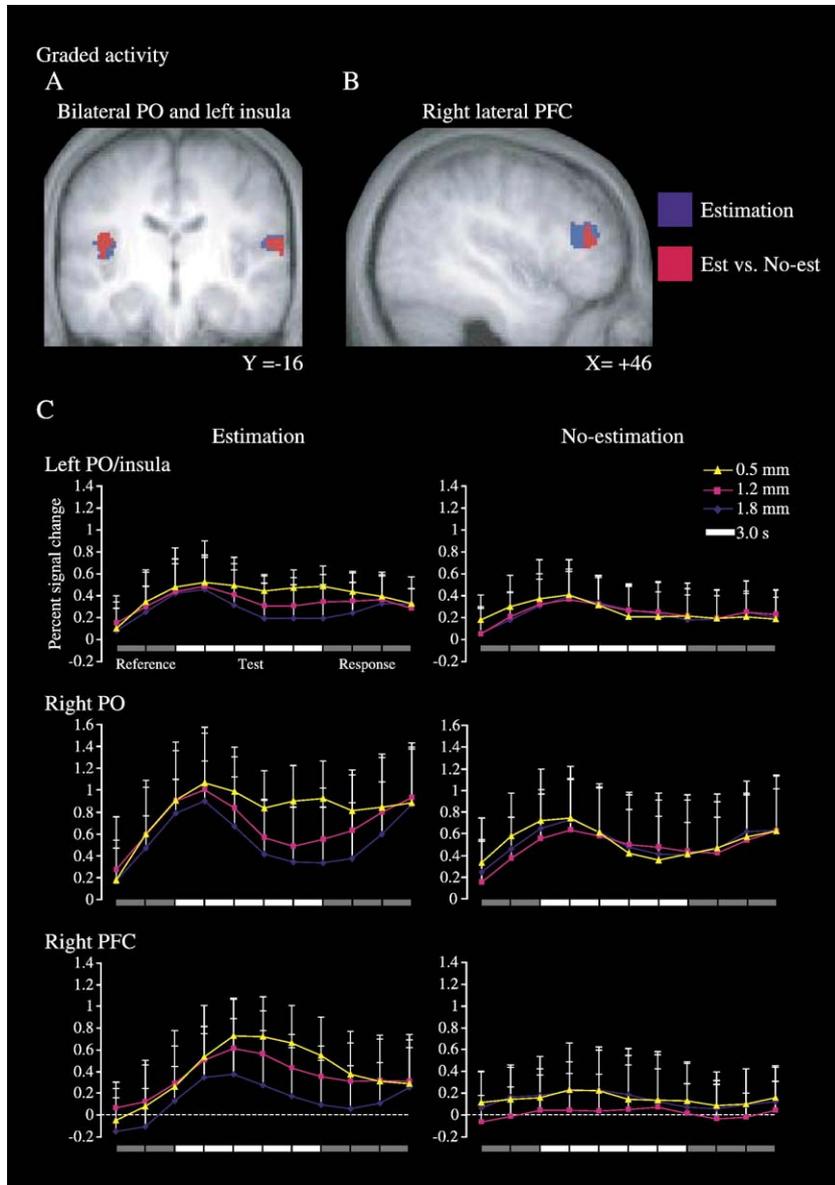


Fig. 4. (A and B) Statistical parametric maps of parametric factorial analysis of negatively graded activity during the estimation condition (Estimation, blue). More negatively graded activity during estimation than the no-estimation condition was superimposed on the blue areas (Est vs. No-est, red). PO, parietal operculum; PFC, prefrontal cortex. (C) Time series of percent signal change in the estimation and no-estimation tasks. Each data point indicates the percent signal change in each spatial period of each task. Error bars indicate SD.

confirm the current roughness rating with their associated roughness sensation, and report the rating by signing with their left hands.

We carefully controlled the task conditions to minimize confounding factors, particularly the motoric components. First, we confirmed using EMG that there was negligible activity of the right flexor digitorum superficialis (FDS) muscle, and hence any change in the vertical force of the stimulated finger was minimized. No overt movement of the body was observed during the test period. Furthermore, our estimation task was designed to exclude possible contaminating effects due to motor execution during the response period; as the test period lasted 18 s, the roughness-estimation process can be evaluated without concern that there was overlap with the planning and response movement. The left-handed response for each scaling number occurs rarely (once every 48 s)

and the training of the left fingers minimized the difficulty of the response with regard to motor planning and preparation.

To discriminate the effect of attention from the neural substrates of the roughness estimation, we employed a parametric factorial design. When recording brain activity during the task, different types of signals correspond to the activation of the attentional mechanism ("source" signal) and its interaction with the sensory systems ("site" signal) (Corbetta, 1998). A source signal would be associated with attentional demand to conduct the estimation, which can be depicted by the estimation vs. no-estimation contrast. This would be recorded in areas that implement the attentional mechanism and hence outside of those for tactile processing. As attention is the mental ability to select relevant stimuli responses, or memories among the others that are behaviorally irrelevant (Corbetta, 1998), the source signal is conceivably condition-

Table 3  
Graded activity in areas activated by the estimation vs. no-estimation

Task	Side	x	y	z	T <sub>2215.1</sub>	Volume	Slope
Estimation							
Lateral prefrontal area	R	50	36	12	5.82	2496	–
No-estimation							
More graded activation in the estimation than no-estimation	n.s.						
Lateral prefrontal area	R	52	38	12	4.5	584	–

R, right hemisphere; L, left hemisphere; x, y, and z are stereotaxic coordinates (mm).

Volume was calculated in mm<sup>3</sup>.  $P < 0.05$  corrected at cluster level. –, negatively graded activities; n.s., not significant.

dependent, unrelated to the stimulus characteristics such as spatial periods of the linear gratings.

On the other hand, a source signal may prime tactile processes for a more efficient response during the estimation condition. Once a stimulus is presented, stimulus analysis may be enhanced by attention. This would produce modulation of tactile processing as well as its related cognitive processing (“site” signal), and this signal would mark the site of the interaction between the source attentional signals and roughness estimation processes (Corbetta, 1998). Hence, the roughness-related activity during the estimation condition, which is not evident during the no-estimation condition, should represent the interaction of the source attentional signals with the tactile estimation processing.

The roughness-related response was observed in the bilateral PO, insula and right prefrontal cortex during the estimation condition but not during the no-estimation condition. This supports our hypothesis that these areas constitute a network for the tactile roughness estimation. It is notable that the right prefrontal cortex with roughness-related response is distinctive from the other part of the anterior prefrontal areas that showed activation by the estimation or no-estimation tasks (Table 1 and Fig. 3). The latter may be related to nonspecific attentional demands such as the response after the stimulation. This finding indicates the effectiveness of our parametric factorial approach.

#### Parietal operculum and insula

The PO is known to contain the secondary somatosensory area (SII), which directly connects not only with the ventral posterior nucleus of the thalamus (Friedman and Murray, 1986; Zhang et al., 2001a,b), but also with the primary somatosensory cortex (SI) in non-human primates (Burton et al., 1995; Krubitzer and Kaas, 1990). Electrical stimulation of the human median nerve causes synchronized activity in the neurons of SII (contralateral) 20–30 ms after stimulation, which is coincident with the first responses generated in SI (Karhu and Tesche, 1999).

It has been proposed that the PO is specifically involved in roughness discrimination. A patient with a tumor compressing the PO and insula demonstrated relatively poor ability to discriminate the roughness of abrasives (Greenspan and Winfield, 1992). Roland et al. (1998) showed that roughness discrimination of textures that varied in spatial period and depth specifically increased the regional cerebral blood flow (rCBF) in the PO, as compared with length or shape discrimination (Ledberg et al.,

1995). In particular, the left lateral PO is proposed as an area for roughness discrimination (Ledberg et al., 1995). SII is also a likely site for tactile memory processes (Burton and Sinclair, 2000). The PO of a macaque monkey has strong direct reciprocal connections with the lateral prefrontal area (area 46) (Preuss and Goldman-Rakic, 1989). Furthermore, SII neurons in non-human primates showed sustained activity during the early delayed period between successively presented vibrotactile stimuli (Romo and Salinas, 2003). Collectively, the PO and insula may play a role in roughness estimation in concert with the lateral prefrontal cortex.

We utilized roughness-related activation as an indicator of the processing underlying tactile estimation. There are several studies indicating that selective attention to a specific feature of a stimulus causes a specific cortical area to facilitate the extraction of the specific sensory information important for the task. In the visual system, viewing a visual stimulus with selective attention to a specific feature (for example, color and motion) activated the specific cortical areas depending on the feature when compared with the identical task without directed selective attention (Corbetta et al., 1991). The perception of coarse textures can be coded by slowly adapting type I (SAI) peripheral fibers as SAI changes in spatial variation (Hsiao et al., 1993); finer textures may be coded as stochastic spatial variation (Johnson et al., 2002; Yoshioka et al., 2001). An alternative interpretation, suggested by the psychophysical data for roughness perception, proposes a two-channel texture code, with Fast adapting type II (FAII) units coding fine surfaces and SAI units coding coarse textures (Hollins et al., 2001, 2002). Some of these peripheral fibers may carry tactile cues important for roughness estimation such as vibration frequency. Vibratory frequency has an inverse relationship with the spatial period of

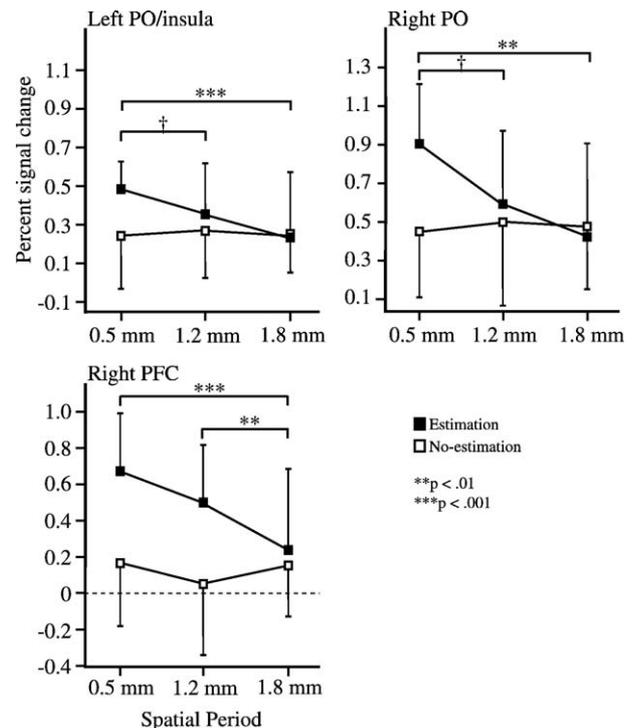


Fig. 5. VOI analyses. The mean percent signal changes in each area are shown. †Indicates a non-significant trend ( $P < 0.07$ ). Error bars indicate SD.

gratings. The frequency of the vibratory stimulus is positively related to the volume of activated areas in the PO and insula (Francis et al., 2000; Harrington and Hunter Downs, 2001). Hence, the negatively graded activity in the PO and insula during the roughness estimation may represent tactile cues such as vibratory frequency. This speculation is in accordance with the idea that the attentional modulation of the PO might represent the selected version of the external world (Mima et al., 1998), which is important for the tactile working memory mechanism (Hamalainen et al., 2002). Burton and Sinclair (2000) also argued that tactile attention biases processing in the somatosensory cortex through amplification of responses to relevant features of selected stimuli.

On the other hand, vibrotactile amplitude of our linear gratings varies less than vibrotactile frequency does across spatial periods. This may explain why we did not observe graded activation in the primary somatosensory cortex, irrespective of the presence of the roughness estimation, given that Nelson et al. (2004) showed that higher vibrotactile amplitude produces higher activation in SI.

#### *Lateral prefrontal cortex*

Area 46 in primates is well known to be a crucial part of the network that mediates working memory (Curtis and D'Esposito, 2003; Goldman-Rakic, 1988). The human lateral prefrontal area was activated during a task requiring subjects to discriminate between speeds of a rotating brush on the palmar surface of the right hand (Bodegard et al., 2000). It also was activated during the haptic discrimination of the relative oblongness of sequentially presented parallelepipeds (Stoeckel et al., 2003). These results suggest that the lateral prefrontal area might be crucial for the comparison of successively presented tactile stimuli.

Our study extends these previous results by showing that these areas are important for scaling the magnitude of roughness in comparison with past sensory experience. The negatively graded response in this area might derive from sensory information coming via the PO or insula, which also showed negatively graded responses. Area 46 in the macaque monkey has strong and direct reciprocal connections with the PO (Preuss and Goldman-Rakic, 1989). In addition, activity of neurons in the lateral prefrontal area, as well as the PO, was related to the vibratory frequency when non-human primates judged the relative flutter frequency of the first of two vibrotactile stimuli presented in succession with a temporal delay between them (Romo and Salinas, 2003; Romo et al., 1999). This suggests that vibratory frequency might be represented not only in sensory areas but also in the lateral prefrontal area in order to differentiate successively presented vibratory stimuli. Therefore, it is plausible that extracted sensory cues (such as vibratory frequency from the PO and insula) are represented in the lateral prefrontal area to scale the roughness percept.

Another possible role for the prefrontal cortex in the tactile estimation would be sensory gating. Staines et al. (2000) found that the sensory-evoked potential by the cutaneous input was modulated (sensory gating) by the relevance of the cutaneous information for the subsequent motor task. This indicates the importance of the context within which the stimuli are interpreted. They further speculated that modulation of activity in the somatosensory cortex to task relevancy could be in part regulated at the level of the thalamic reticular nucleus that receives corticothalamic fibers from the prefrontal cortex (area 9) (Staines et al., 2002). In this study, we presented tactile stimuli passively without finger movement. Furthermore, neither higher activation nor graded activation was

observed in the thalamus in the roughness estimation. Hence, the graded activity in the prefrontal cortex, PO, and insula is unlikely to be occurred by sensory gating.

#### *Gender difference*

We did not find any conspicuous gender difference in the present study. Women is known to outperform men in tactile acuity (Goldreich and Kanics, 2003; Van Boven et al., 2000). The heightened tactile acuity of women may be attributable to greater skin compliance (Woodward, 1993), and hence peripheral in origin. Gender difference, if any, is unlikely to affect the graded activity in the prefrontal cortex, PO, and insula.

#### **Conclusion**

The bilateral PO, left insula and right lateral prefrontal area showed more negatively graded responses during the estimation task than the no-estimation task which yielded no graded response. Among these cortical areas, the right lateral prefrontal area showed a significantly higher mean response across spatial periods during the estimation task when compared with the no-estimation task. We concluded that the lateral prefrontal area might play an important cognitive role during the tactile estimation of surface roughness, whereas the PO and insula might represent the extracted sensory information that is important for estimating surface roughness.

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#### **References**

- Bodegard, A., Geyer, S., Naito, E., Zilles, K., Roland, P.E., 2000. Somatosensory areas in man activated by moving stimuli: cytoarchitectonic mapping and PET. *NeuroReport* 11, 187–191.
- Brett, M., Anton, J.-L., Valabregue, R., Poline, J.-B., 2002. Region of interest analysis using an SPM toolbox. Presented at the 8th International Conference on Functional Mapping of the Human Brain, Sendai, Japan.
- Buchel, C., Holmes, A.P., Rees, G., Friston, K.J., 1998. Characterizing stimulus–response functions using nonlinear regressors in parametric fMRI experiments. *NeuroImage* 8, 140–148.
- Burton, H., Sinclair, R.J., 2000. Attending to and remembering tactile stimuli: a review of brain imaging data and single-neuron responses. *J. Clin. Neurophysiol.* 17, 575–591.
- Burton, H., Videen, T.O., Raichle, M.E., 1993. Tactile-vibration-activated foci in insula and parietal-opercular cortex studied with positron emission tomography: mapping the second somatosensory area in humans. *Somatosens. Motor Res.* 10, 297–308.
- Burton, H., Fabri, M., Alloway, K., 1995. Cortical areas within the lateral sulcus connected to cutaneous representations in areas 3b and 1: a revised interpretation of the second somatosensory area in macaque monkeys. *J. Comp. Neurol.* 355, 539–562.
- Burton, H., MacLeod, A.M., Videen, T.O., Raichle, M.E., 1997. Multiple foci in parietal and frontal cortex activated by rubbing embossed grating

- patterns across fingerpads: a positron emission tomography study in humans. *Cereb. Cortex* 7, 3–17.
- Coghill, R.C., Talbot, J.D., Evans, A.C., Meyer, E., Gjedde, A., Bushnell, M.C., Duncan, G.H., 1994. Distributed processing of pain and vibration by the human brain. *J. Neurosci.* 14, 4095–4108.
- Corbetta, M., 1998. Frontoparietal cortical networks for directing attention and the eye to visual locations: identical, independent, or overlapping neural systems? *Proc. Natl. Acad. Sci. U. S. A.* 95, 831–838.
- Corbetta, M., Miezin, F.M., Dobmeyer, S., Shulman, G.L., Petersen, S.E., 1991. Selective and divided attention during visual discriminations of shape, color, and speed: functional anatomy by positron emission tomography. *J. Neurosci.* 11, 2383–2402.
- Curtis, C.E., D'Esposito, M., 2003. Persistent activity in the prefrontal cortex during working memory. *Trends Cogn. Sci.* 7, 415–423.
- Francis, S.T., Kelly, E.F., Bowtell, R., Dunseath, W.J., Folger, S.E., McGlone, F., 2000. fMRI of the responses to vibratory stimulation of digit tips. *NeuroImage* 11, 188–202.
- Friedman, D.P., Murray, E.A., 1986. Thalamic connectivity of the second somatosensory area and neighboring somatosensory fields of the lateral sulcus of the macaque. *J. Comp. Neurol.* 252, 348–373.
- Friston, K.J., Ashburner, J., Frith, C.D., Heather, J.D., Frackowiak, R.S.J., 1995a. Spatial registration and normalization of images. *Hum. Brain Mapp.* 2, 165–189.
- Friston, K.J., Holmes, A.P., Worsley, K.J., Poline, J.B., Frith, C.D., Frackowiak, R.S.J., 1995b. Statistical parametric maps in functional imaging: a general linear approach. *Hum. Brain Mapp.* 2, 189–210.
- Friston, K.J., Holmes, A.P., Poline, J.B., Price, C.J., Frith, C.D., 1996. Detecting activations in PET and fMRI: levels of inference and power. *NeuroImage* 4, 223–235.
- Friston, K.J., Price, C.J., Buchel, C., Frackowiak, R.S.J., 1997. A taxonomy of study design. In: Frackowiak, R.S.J., Friston, K.J., Frith, C.D., Dolan, R.J., Mazziotta, J.C. (Eds.), *Human Brain Function*. Academic Press, San Diego, pp. 141–159.
- Goldman-Rakic, P.S., 1988. Topography of cognition: parallel distributed networks in primate association cortex. *Annu. Rev. Neurosci.* 11, 137–156.
- Goldreich, D., Kanics, I.M., 2003. Tactile acuity is enhanced in blindness. *J. Neurosci.* 23, 3439–3445.
- Greenspan, J.D., Winfield, J.A., 1992. Reversible pain and tactile deficits associated with a cerebral tumor compressing the posterior insula and parietal operculum. *Pain* 50, 29–39.
- Hamalainen, H., Hiltunen, J., Titievskaja, I., 2002. Activation of somatosensory cortical areas varies with attentional state: an fMRI study. *Behav. Brain Res.* 135, 159–165.
- Harada, T., Saito, D.N., Kashikura, K., Sato, T., Yonekura, Y., Honda, M., Sadato, N., 2004. Asymmetrical neural substrates of tactile discrimination in humans: a functional magnetic resonance imaging study. *J. Neurosci.* 24, 7524–7530.
- Harrington, G.S., Hunter Downs III, J., 2001. FMRI mapping of the somatosensory cortex with vibratory stimuli. Is there a dependency on stimulus frequency? *Brain Res.* 897, 188–192.
- Hollins, M., Bensmaia, S.J., Washburn, S., 2001. Vibrotactile adaptation impairs discrimination of fine, but not coarse, textures. *Somatosens. Motor Res.* 18, 253–262.
- Hollins, M., Bensmaia, S.J., Roy, E.A., 2002. Vibrotactile and texture perception. *Behav. Brain Res.* 135, 51–56.
- Hsiao, S.S., Johnson, K.O., Twombly, I.A., 1993. Roughness coding in the somatosensory system. *Acta Psychol. (Amst.)* 84, 53–67.
- Johnson, K.O., Hsiao, S.S., Yoshioka, T., 2002. Neural coding and the basic law of psychophysics. *Neuroscientist* 8, 111–121.
- Karhu, J., Tesche, C.D., 1999. Simultaneous early processing of sensory input in human primary (SI) and secondary (SII) somatosensory cortices. *J. Neurophysiol.* 81, 2017–2025.
- Krause, T., Kurth, R., Ruben, J., Schwiemann, J., Villringer, K., Deuchert, M., Moosmann, M., Brandt, S., Wolf, K., Curio, G., Villringer, A., 2001. Representational overlap of adjacent fingers in multiple areas of human primary somatosensory cortex depends on electrical stimulus intensity: an fMRI study. *Brain Res.* 899, 36–46.
- Krubitzer, L.A., Kaas, J.H., 1990. The organization and connections of somatosensory cortex in marmosets. *J. Neurosci.* 10, 952–974.
- Ledberg, A., O'Sullivan, B.T., Kinomura, S., Roland, P.E., 1995. Somatosensory activations of the parietal operculum of man. A PET study. *Eur. J. Neurosci.* 7, 1934–1941.
- Mima, T., Nagamine, T., Nakamura, K., Shibasaki, H., 1998. Attention modulates both primary and second somatosensory cortical activities in humans: a magnetoencephalographic study. *J. Neurophysiol.* 80, 2215–2221.
- Nelson, A.J., Staines, W.R., Graham, S.J., McIlroy, W.E., 2004. Activation in SI and SII: the influence of vibrotactile amplitude during passive and task-relevant stimulation. *Brain Res. Cogn. Brain Res.* 19, 174–184.
- Oldfield, R.C., 1971. The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia* 9, 97–113.
- Preuss, T.M., Goldman-Rakic, P.S., 1989. Connections of the ventral granular frontal cortex of macaques with perisylvian premotor and somatosensory areas: anatomical evidence for somatic representation in primate frontal association cortex. *J. Comp. Neurol.* 282, 293–316.
- Roland, P.E., O'Sullivan, B., Kawashima, R., 1998. Shape and roughness activate different somatosensory areas in the human brain. *Proc. Natl. Acad. Sci. U. S. A.* 95, 3295–3300.
- Romo, R., Salinas, E., 2003. Flutter discrimination: neural codes, perception, memory and decision making. *Nat. Rev., Neurosci.* 4, 203–218.
- Romo, R., Brody, C.D., Hernandez, A., Lemus, L., 1999. Neuronal correlates of parametric working memory in the prefrontal cortex. *Nature* 399, 470–473.
- Staines, W.R., Brooke, J.D., McIlroy, W.E., 2000. Task-relevant selective modulation of somatosensory afferent paths from the lower limb. *Neuroreport* 11, 1713–1719.
- Staines, W.R., Graham, S.J., Black, S.E., McIlroy, W.E., 2002. Task-relevant modulation of contralateral and ipsilateral primary somatosensory cortex and the role of a prefrontal-cortical sensory gating system. *NeuroImage* 15, 190–199.
- Stoessel, M.C., Weder, B., Binkofski, F., Buccino, G., Shah, N.J., Seitz, R.J., 2003. A fronto-parietal circuit for tactile object discrimination: an event-related fMRI study. *NeuroImage* 19, 1103–1114.
- Talairach, J., Tournoux, P., 1988. *A Co-Planar Stereotaxic Atlas of a Human Brain*. Thieme, Stuttgart.
- Van Boven, R.W., Hamilton, R.H., Kauffman, T., Keenan, J.P., Pascual-Leone, A., 2000. Tactile spatial resolution in blind Braille readers. *Neurology* 54, 2230–2236.
- Woodward, K.L., 1993. The relationship between skin compliance, age, gender, and tactile discriminative thresholds in humans. *Somatosens. Motor Res.* 10, 63–67.
- Worsley, K.J., Friston, K.J., 1995. Analysis of fMRI time-series revisited—Again. *NeuroImage* 2, 173–181.
- Yoshioka, T., Gibb, B., Dorsch, A.K., Hsiao, S.S., Johnson, K.O., 2001. Neural coding mechanisms underlying perceived roughness of finely textured surfaces. *J. Neurosci.* 21, 6905–6916.
- Zhang, H.Q., Murray, G.M., Coleman, G.T., Turman, A.B., Zhang, S.P., Rowe, M.J., 2001a. Functional characteristics of the parallel SI- and SII-projecting neurons of the thalamic ventral posterior nucleus in the marmoset. *J. Neurophysiol.* 85, 1805–1822.
- Zhang, H.Q., Zachariah, M.K., Coleman, G.T., Rowe, M.J., 2001b. Hierarchical equivalence of somatosensory areas I and II for tactile processing in the cerebral cortex of the marmoset monkey. *J. Neurophysiol.* 85, 1823–1835.